3-D Thermal and Seismic Structure of Slab and Plate Interface in Northern Cascadia

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Investigations undertaken

(1) 2-D numerical modeling of flow and temperature in Northern Cascadia's mantle wedge and backarc. (2) Preliminary 3-D local-earthquake tomography and preparation for teleseismic inversion. (3) Study of mechanical impact of metamorphic densification of subducting crust on warm slab earthquakes. (4) Detection and study of non-volcanic tremors in association with silent slips.

Results

1. Thermal model

As a first step in thermal modeling, we developed 2-D finite element models to test the effects of linear and non-linear mantle wedge rheology, boundary conditions, and temperature-dependent thermal conductivity. At subduction zones, geophysical and geochemical observations indicate that the arc and backarc regions are very hot, in spite of the cooling effects of a subducting plate. At the well-studied Cascadia subduction zone, high temperatures in the backarc persist for over 500 km into the backarc, with little lateral variation. These high temperatures are even more surprising due to the juxtaposition of the hot Cascadia backarc against the thick, cold North America craton lithosphere. Local heat sources appear to be negligible and thus, mantle flow is required to transport heat into the wedge and backarc. We address the heat budget at a subduction zone and examine the thermal consequences of mantle flow induced by traction along the top of the subducting plate. For traction-driven flow, the thermal structure of the wedge is primarily determined by the mantle rheology and the assumed thermal conditions at the landward limit of the backarc. To get high temperatures in the wedge, it is necessary for flow to mine heat from depth. Flow within an isoviscous wedge is too slow to transport a significant amount of heat into the wedge corner. With a more realistic stress- and temperature-dependent wedge rheology, flow is focused into the wedge corner, resulting in rapid flow upward toward the corner and enhanced temperatures below the arc, compatible with temperatures required for arc magma generation. However, this strong flow focusing produces a nearly stagnant region in the shallow backarc mantle, where temperatures and heat flow are much lower than observed. None of the models of simple traction-driven flow were able to simultaneously produce high temperatures beneath the volcanic arc and throughout the backarc. We argue that high temperatures throughout the backarc, particularly in areas that have not undergone extension, provide an important constraint on wedge dynamics. One way to produce hot and isothermal conditions in the backarc is through vigorous small-scale free convection in a low viscosity upper mantle.

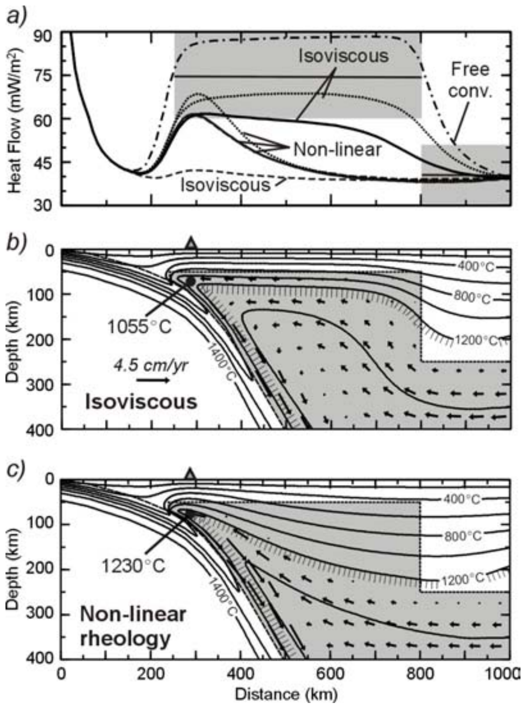

Figure 1. Cascadia thermal models with a rigid 250 km thick craton lithosphere located 800 km from the trench. a) Modelled surface heat flow for models without a craton (dashed), with a craton (solid), and craton models with a free-slip boundary condition between the wedge and over-riding lithosphere (dotted). The dot-dashed line is the heat flow for a proxy model in which the effects of extremely vigourous free convection (Nusselt number of 1000) are simulated. For all models, a cool craton geotherm was prescribed to the landward boundary. b) Thermal model cross-section for an isoviscous wedge. The shaded region indicates where viscous flow was allowed; arrows show flow direction. (c) same as (b), but for a non-linear wedge rheology.

2. Tomography

In preparation for a combine 3-D tomogaphic model using both local and teleseismic events, we have been testing various local-earthquake inversions while preparing teleseismic data. A large-scale controlled source 3-D tomographic inversion, utilizing approximately 500,000 picks from SHIPS-98 experiment, was performed to construct a detailed (1 km cell size) velocity model of the upper crust (<15 km) beneath southwestern

British Columbia and northern Washington. This velocity model maps the lateral velocity heterogeneities beneath the study area. The controlled source data is presently being supplemented with earthquake picks for joint inversion of earthquake and controlled source data. The resultant velocity model from the joint inversion would map the lower crust and the fore arc upper mantle structures down to ~70 km depth. Concurrently tele-seismic arrivals beneath southern British Columbia are being picked for performing tele-seismic tomography to map the geometry of the subducting Juan de Fuca plate. The tele-seismic picks will be corrected for arrival time to remove the effects of crust using the previously constructed *a priori* crustal velocity model. Tele-seismic tomography will be implemented as an incremental process by enlarging the study area in subsequent inversions

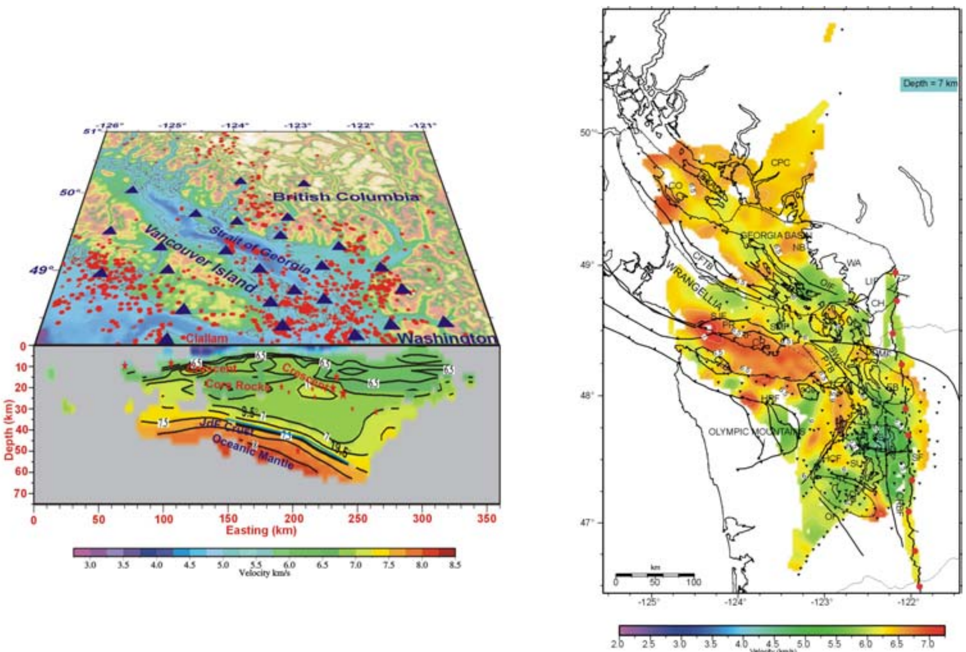

Figure 2. Left: One vertical cross section of a 3-D P-wave tomography velocity model for Northern Cascadia using local earthquakes and controlled source. On the map, blue triangles are seismic stations, and red dots are earthquakes used. Right: One slice at 7 km depth of a preliminary large-scale 3-D P-wave velocity model for southwestern British Columbia and northern Washington, using controlled sources.

3. Slab mechanics

We have conducted research on the mechanical effects of rock densification during the metamorphic transformation of meta-basalt to eclogite. During subduction, dehydration may facilitate earthquake rupture in both the slab crust and slab mantle. The up to 15% rock densification that accompanies the metabasalt-eclogite transformation is expected to have several mechanical consequences. In warm slabs such as Cascadia and Nankai, this transformation and mantle serpentine breakdown begin at rather shallow depths (30 - 50 km). For kinetic reasons, densification begins in a thin layer along the top of the slab. Volume reduction gives rise to an equivalent stretching force in the thin layer in all slab-parallel directions, activating existing faults and developing new fractures. Analogous to a weak layer sandwiched between, and bonded to, two strong layers under stretching, fracture spacing in the weak layer scales with the layer thickness. The theory and our finite element modeling predict that the densified thin layer must be "shattered". The shattered upper crust may have numerous small earthquakes but does not favor large ruptures. In contrast, the much more uniform lower crust and mantle can host larger ruptures, although seismic ruptures occur only in the limited hydrated parts. This explains the observation that relatively few earthquakes deeper inside the slab tend to have larger magnitudes than those just below the slab surface. For example, three recent damaging events (1999 Oaxaca, Mexico; 2001 Geiyo, Nankai; 2001 Nisqually, Cascadia) in warm slabs all occurred in the lower crust or mantle. Because of the shattered state of the subducting crust, the large Nisqually earthquake must have ruptured the mantle. That rupture size is not limited by the thickness of the slab crust has important hazard implications. The densification is on average a steady state process. However, at the fracture scale, the process is highly nonlinear, and there must be small fluctuations due to mechanical and kinetic irregularities. Readjustments of high-fluid-pressure rocks in and above the shattered subducting crust in responses to such densification fluctuations may be responsible for episodic lower-frequency tremors recorded at the Cascadia and Nankai subduction zones. Transient modifications of slab-surface topography and roughness in the same process may trigger silent slips along the plate interface.

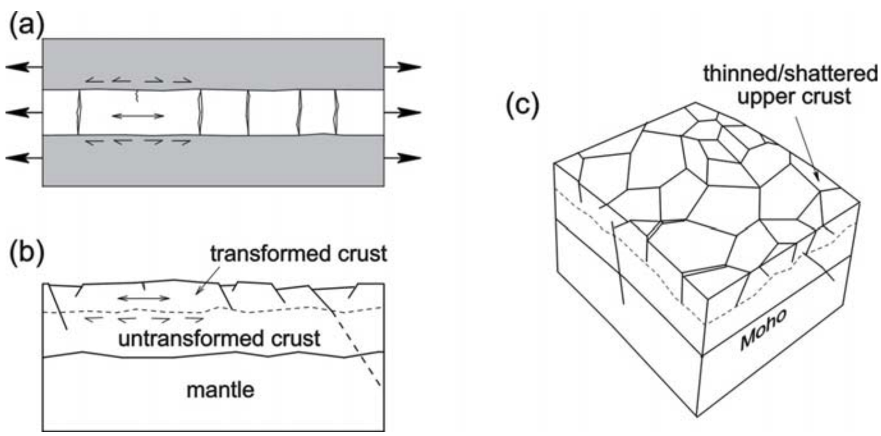

Figure 3. (a) Spacing of opening fractures in a weak layer between, and bonded to, two strong layers. Fracture infilling will occur if the spacing is large, because the unfractured segment is pulled apart by tractions along layer interfaces. (b) Conceptual model of fault spacing in the densified part of the subducting crust. (c) Shattered upper crust in which seismic rupture propagation will be limited.

4. Episodic tremor and slip

Repeated slow slip events observed on the deeper interface of the northern Cascadia subduction zone, at first thought to be silent, have now been found to have unique, non-earthquake, seismic signatures. Tremor-like seismic signals have been found to correlate temporally and spatially with slip events identified from crustal motion data spanning the past six years. During the period between slips, tremor activity is minor or non-existent.

We call this associated tremor and slip phenomenon Episodic Tremor and Slip (ETS) and propose that ETS activity can be used as a real-time indicator of stress loading of the Cascadia megathrust earthquake zone. The discovery has been reported in a Science paper by Rogers and Dragert [2003], and we are in the process of better characterizing the ETZ and understanding its implications to slab thermal, mechanical, and petrological processes.

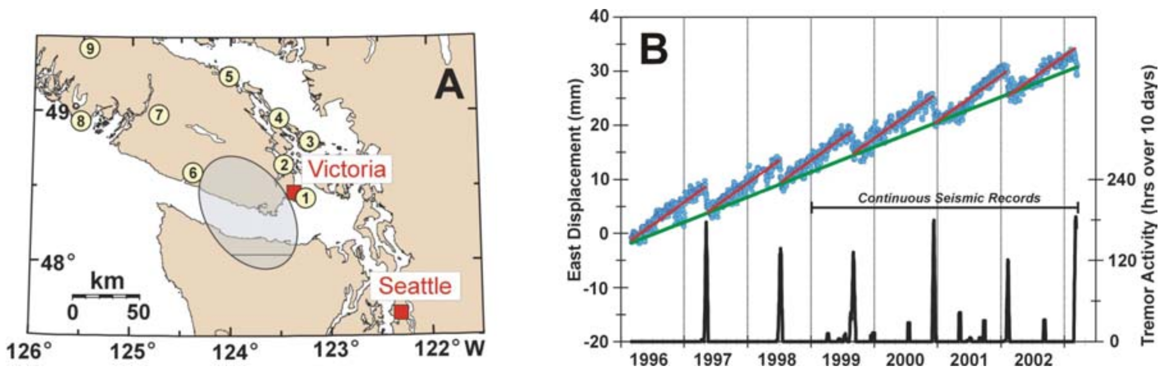

Figure 4. (A) Map of seismic network sites (numbered circles) and approximate source region (shaded ellipse) for tremors used for correlation with observed slips. Note that both tremors and slips have been observed to migrate parallel to the strike of the subduction zone to the south, through, and to the north of this shaded region. (B) Comparison of slip and tremor activity observed for the Victoria area. Blue circles show day-by-day change in the east component of the GPS site ALBH (Victoria) with respect to Penticton which is assumed fixed on the North America plate. Continuous green line shows the long-term (interseismic) eastward motion of the site. Red saw-tooth line segments show the mean elevated eastward trends between the slip events which are marked by the reversals of motion every 13 to 16 months. Bottom graph shows the total number of hours of tremor activity observed for southern Vancouver Island within a sliding 10-day period (complete annual records examined from 1999 onward). 10 days corresponds to the nominal duration of a slip event. The graph ends Mar. 10, 2003, with the slip and tremor activity that was predicted for the spring of 2003..

Non-technical Summary

This project is designed to investigate what controls the damaging earthquakes within the subducting Juan de Fuca plate beneath the Pacific Northwest. Thermally controlled metamorphic processes as well as tectonic stresses are considered responsible for the generation of these earthquakes. To have a better understanding of the thermo-petrological process, we are developing 3-D tomography models using both local and remote earthquakes to constrain the rock properties in and around the slab and numerical models to understand the 3-D thermal field. We also explore the implication of episodic tremors and slips in the subduction zone on slab processes and compare the thermal and stress fields with the similar Nankai subduction zone in SW Japan.

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